FLOW AND TURBULENCE CHARACTERISTICS OF SEPARATED FLOWS WITH ACTIVE CONTROL

Final Technical Report

by

J H Whitelaw

May 1998

United States Army,

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London, England

CONTRACT NUMBER N68171-97-C-9009

Imperial College of Science, Technology & Medicine

SUMMARY OF RESEARCH

The contract was signed on 19th December 1996 and work began officially on that date although considerable preparations had already been made. As indicated in the Proposal, it was undertaken mainly by graduate students working with the Principal Investigator and with contributions from existing faculty and visiting staff. In this last category, Drs L Khezzar and S Sivasegaram, who are former graduate students of Imperial College, were brought from their Universities in Oman and Sri Lanka to assist with laser measurements and with acoustic and control aspects of the project, Seven interim reports have been provided together with eight technical reports.

The objectives of the research were to provide new physical information of steady and unsteady premixed combustion, so as to assist the development of models and to provide explanations, in terms of local flow properties, of physical phenomena observed in unsteady flows. The results of the experiments should be prepared to allow interaction with direct numerical simulations of unsteady conservation equations and to guide the development and use of methods which involve additional physical assumptions, such as those which make use of time-averaged equations and large-eddy simulations, and are more suited to engineering applications. Further investigations of active control of combustion oscillations were to be undertaken.

The tasks described in the proposal and repeated in the Appendix to this report have been completed in good time and with some success. Thus, the various technical reports provide detailed measurements of velocity characteristics in a plane sudden-expansion flow over a range of Reynolds numbers and extensive information of the corresponding combusting flows over a range of equivalence ratios from the lean to the rich limit. These detailed measurements will allow their use by those who wish to evaluate and improve their calculation methods.

Emphasis has been placed on defining the flammability and stability limits and on enhanced understanding of the processes of blow-off and extinction. Careful observation of the related processes revealed a tendency towards oscillations with frequencies much lower than those associated with acoustic or bulk-mode frequencies of the duct and with modulation rather than the single-frequency oscillations associated with equivalence Ratios between around 0.75 and 1.2. Active control of oscillations proved to be successful within a limited range of equivalence ratios and flow rates and the less successful results with high heat loads appeared to be associated with the existence of more than a single frequency.

A second combustor was constructed to allow consideration of the same variables in a round sudden expansion flow and similar results were obtained apart from the processes which led to extinction of very lean mixtures where the low frequency oscillation tended to be axial in contrast to the transverse oscillations observed with the plane sudden expansion.

Two further arrangements, one a model of the combustor of a land-based gas turbine with an annular main flow and a central pilot flow and the other a model which involved swirl stabilisation, were constructed and examined. In the first arrangement, the movement of flame stabilisation from the annular ring to the back step was particularly notable and, in the latter, it was found that the position of stabilisation also moved but this time axially

with increasing load so that the fixed position of the actuator for active control proved to be satisfactory for some load conditions and less so for others.

The objectives have been more than fulfilled and remaining tasks include;

further examination of the nature of extinction of lean and rich flames stabilised on bluff bodies and of the translation of flame stabilisation with boundary conditions.

consideration of ways in which active control can be improved by the development of better sensors, actuators and controllers. With the possibility of moving regions of flame stabilisation, it will be necessary to construct sensor arrays, to evaluate the !best position for particular actuators, to provide a methodology which will allow the actuator to change its performance and perhaps position, and to devise controllers which will operate with lower amplitudes and with modulated signals.

CONDUCT OF TASKS SPECIFIED IN THE PROPOSAL

This section reviews the research in terms of the four tasks of Appendix A and in number order. The tasks are identified and a summary of the findings reported in each case. More detail is available in the reports referenced here and made available with the interim reports. All tasks have been successfully addressed and the following section addresses the new questions which arise from the research and the means by which they may be answered.

1. The required two-dimensional, plane ducted flow with a sudden expansion, upstream contraction, and loudspeaker at upstream end, was constructed and tested with air flow and with premixed methane gas and air flows. The arrangement is shown in figure 1 together with the axisymmetric configuration and actuators used in later tests.

Experiments were performed to quantify the isothermal flow downstream of a plane sudden expansion and included visualisation, and measurements of pressure and velocity. Samples of the visualisation and velocity measurements are provided in figures 2 and 3 and demonstrate the asymmetry of the flow, with unequal recirculation zones, at all Reynolds numbers above 600. The extent of this asymmetry did not vary with flow rate provided the inlet flow was turbulent and was reduced by coupling the pressures between the two recirculation regions, and by suppressing the shear layer instability responsible for this asymmetry by imposing oscillations at the half-wave or full-wave frequency of the duct and by combustion. In the isothermal flow, the ratio of the lengths of the two recirculation regions tended to be an uneven integer greater than unity. These results are consistent with the findings of earlier investigations with different expansion ratios and are provided in considerable detail.

Reacting flows were characterised in terms of the frequency and amplitude of pressure oscillations and similar measurements were carried out with sudden expansions in round ducts with an area ratio of 2.25 for purposes of comparison, and the amplitudes in the both ducts were comparable for the same heat release and upstream to downstream duct length ratio. Plane ducts with an acoustically open upstream end gave rise to oscillations with frequency around 200 Hz, corresponding to a half-wave in the entire duct; the amplitude was greatest when the quarter-wave frequencies of the duct upstream and

downstream of the step were the same. In ducts with a closed upstream end, the oscillations at low flow rates were associated with the quarter-wave but for upstream velocities greater than around 12 m/s it gave way to the three-quarter wave also in the entire duct at 200 Hz which had maximum amplitude when the half-wave frequency of the upstream duct length matched the quarter-wave frequency of the downstream duct. Further details are available in reference 1 and in other references.

2. The measurement techniques used with the reacting flows included still and fast photography, laser velocimetry, small-diameter digitally-compensated thermocouples and flame ionisation and chemiluminescence for the measurement of concentrations of unburned hydrocarbons and nitric oxides, respectively. Active control was achieved with a loudspeaker and an adaptive arrangement to measure the frequency and phase and to instruct a loudspeaker to impose oscillations.

These techniques were familiar to Drs. Khezzar and Sivasegaram so that no difficulties were expected or encountered. In contrast, considerable efforts were made to arrange a Rayleigh-scattering system for the measurement of temperature and proved to be unsuccessful, as described in reference 2. The instrumentation worked satisfactorily in open flames with lean mixtures but the combination of confined flows with their inevitable reflections and the need to measure over a wide range of equivalence ratios proved to be impossible with the available instrumentation. The arrangement of instrumentation is shown on figure 4.

Considerable efforts were also expended on the development of flow visualisation methods and an arrangement for the detection of CH radicals. In the former, the emphasis was on the use of surface coatings of oil and pigment to provide a cheap and rapid way to examine single- and two-phase flows, reference 5, and, in the latter, a system was developed to allow the better observation of the patterns of heat release as represented by the chemiluminescence of the CH radicals, reference 9. The first technique has been used successfully with the isothermal flows and particularly to examine the regions of recirculation downstream of the sudden expansion and the latter has so far been applied only to open flames but it will shortly be used to examine the stabilisation patterns of the present flames with emphasis on equivalence ratios close to extinction.

3. As outlined above and described in detail in reference 4, the reacting flow was arranged with several Reynolds numbers and examined by flow visualisation as a preliminary to detailed measurements which began with the isothermal flows. Detailed measurements were made in turbulent flows with an area expansion ratio of 2.86 and at a Reynolds number of 20,000, and the combusting flows comprised premixed methane and air over a range of equivalence ratios, with emphasis on values of 0.72 and 0.92, which gave rise to smooth and rough combustion, respectively, and measurements include those of pressure, velocity, temperature, species concentrations, stability limits and of the ability to modify the amplitude of acoustic oscillations.

The results showed that the asymmetry present in the isothermal flow was eliminated and the ratio of the two opposing recirculation zones was less than 1.2 with the combusting flow. The time-averaged lengths of the recirculation zones with rough combustion were around four times shorter than those with smooth combustion, resulting in flame stabilisation closer to the expansion and in uniform mean temperature profiles by 7 step heights downstream, in contrast to 11 step heights with smooth combustion.

They also revealed the periodic variation of flame shape, velocities, acceleration, and temperature in sympathy with the dominant pressure oscillation of rough combustion, and the length of the recirculation zones varied from less than 0.5 to 3 step heights. In the isothermal and smooth combusting flows, the maximum rms velocities tended to occur at the maximum gradients of the mean profiles and, in general, skewness and bimodality were absent in the velocity distributions except in the vicinity of reattachment. In contrast, the strongest bimodality in the velocity and temperature distributions with rough combustion was found in the centre of the duct near the expansion plane, which suggests that the main large scale structures were associated with the potential core rather than with the recirculation zones.

Rich and lean limits were established for combustion within the duct and, whereas the flame blew off at the lean limit, it detached from the expansion at the rich limit and stabilised on the flange at the duct exit. Within these limits, and as shown on figure 5, there were ranges of equivalence ratios over which the flame stabilised on one of the two steps with combustion incomplete in the exit plane and quantified by concentrations of unburned hydrocarbons. Oscillations of arbitrary phase imposed with the loudspeaker, narrowed the range of equivalence ratios over which the flame could be stabilised on the sudden expansion, and also reduced the equivalence ratio at which the flame stabilised on both steps thus increasing the range of equivalence ratios over which the lean flame could be operated with complete combustion. These effects increased with amplitude and were greatest when the frequency of the oscillations corresponded to that of the half-wave in the duct, and for a given input voltage, imposed out-of-phase and arbitrarily-phased oscillations at this resonance frequency achieved the same modification of the stability limits. With both smooth combustion and with large-amplitude rough combustion, an increase in the amplitude of flow oscillations, natural or imposed, caused the concentrations of NOx measured at the duct exit to decrease.

This extensive pattern of results of reference 4 more than fulfils the third task. Further details are available in the report and, the subsequent emphasis of the research was related to reacting flows, and in particular the fulfilment of the fourth objective.

4. This task involved four geometric configurations and an extensive range of experiments which included detailed measurements of velocity, temperature, emissions and acoustic characteristics and they are described in references 3, 4, 6, 7 and 8.

Active control of flows with high amplitude of oscillations produced the expected reductions but not over the entire measured range of equivalence ratio as shown on figure

6. Also, imposing the second harmonic of the half-wave frequency with arbitrary phase reduced the amplitude of oscillations associated with rough combustion more than active control over part of the measured range of equivalence ratio and due to intermittent loss of lock associated with more than one frequency.

The above investigation raised two important questions which were, in large part, answered by the additional research of references 6 and 7. The former addressed the ability to control flames in the context of a coaxial flow with lean mixtures in the annulus and the latter of a strongly swirling combustor. In both cases, active control proved to be successful over a wide range of flows but less so at high loads and largely due to the movement of the flame and its region of stabilisation. In the annulus, it was possible for

the flame to stabilise on the back step or on the annulus formed by the central pipe and each arrangement had its range of stable operation but this could not always be predicted a priori so that the location of the sensor and actuator was not always in the correct place. The same situation occurred in the swirl burner of figure 7 in which the flame was stabilised in the swirling flow within the divergent cone and tended to move upstream with increasing swirl and downstream with increasing load. A jet of gaseous fuel was used to provide the out-of-phase oscillations in this case and could be injected from the upstream end and on the centre line or with the flow of air or gaseous fuel into the swirler in this flow. Both choices offered advantages with specific flows but neither provided adequate reduction of combustion oscillations over the complete range of operation, as shown in figure 8.

Thus, it is clear that active control can reduce the amplitude of oscillations by large amounts but has a limited range of successful operation in configurations in which the flame and its region of stabilisation can translate from one position to another. Sensors with a wider remit can readily be envisaged and actuators with greater flexibility in their location of applicability can be envisaged. It is also likely that the controllers will have to be improved and, although a priori knowledge of transfer functions are unlikely, it is possible to devise systems which can operate with lower-amplitude signals and with high amplitude signals which are present with a range of amplitudes and frequencies.

The experiments of reference 8 were performed partly to provide a direct link between axisymmetric and plane flows and partly to extend knowledge of the nature of the flames in the vicinity of the lean and rich flammability limits and particularly close to extinction. In general, the results from the two configurations are similar as can be seen from the flammability and stability limits of figure 9, although it is evident that the axisymmetric arrangement allows slightly greater stability as might be expected from the cold-flow investigations of the recirculation region. Of greater importance, both show similar trends as the equivalence ratio is moved towards the flammability limits with a tendency for the oscillations to change from acoustic to bulk mode to amplitudes and frequencies associated with neither and more likely to be linked to a process of local extinction and relight which is dependent on local time-dependent strain rate and on the chemistry of the fuel. The three actuators of figure 1 were used to control the large-amplitude oscillations in the axisymmetric configuration and it was found that pressure oscillations were most effective when imposed at the pressure antinode. Control by the fuel supply was affected by attenuation of the imposed oscillation and by the large pressure fluctuations close to the antinode.

CONCLUDING REMARKS

The research was conducted in accord with the plan described in the Proposal and extended to consider additional configurations and thereby to provide better understand of aspects of flame stabilisation, naturally occurring oscillations and control.

The main tasks included the design, construction and use of a plane sudden expansion configuration with isothermal and combusting flows and this has been achieved with extensive measurements and a clear description of the acoustic, velocity and temperature characteristics of the flows. This flow also provided information of the merits of active control and revealed the low-frequency, modulated oscillations described above in relation to extinction.

The nature of the oscillations close to the lean flammability limit provides a link with the research of Sardi et al (10 to 13), also supported by the US Army, and in particular with the possibility that lean extinction is a process which can involve many oscillation cycles prior to final extinction. The duration of the process seems to depend on the instantaneous strain rate and on the part of the oscillation cycle so that sequences of local extinction and relight are possible. This strengthens the possibility that active control should be able to extend the lean limit by reducing the strain rate but there is little experience of the application of active control to the low frequency modulated signal observed here with the plane and round sudden expansions

The additional flows, both models of particular combustors used in practice, revealed changes in the position of flame attachment with load and the consequence that a fixed actuator could not give equal performance over the range of loads. The inability to control flows with low amplitude oscillations is of little consequence and this limitation could be removed with a more sophisticated controller. the decline in performance with high load is worrying since most evaluations of active control have been conducted with comparatively low loads. Again, however, there are clear lessons in that the movement of the region of attachment has to be recognised in real time and modifications made to the position of the actuator or its operation.

ACKNOWLEDGEMENTS

The research was supported by the US Army, through a contract let by the US Navy and I am pleased to record my thanks to both organisations and to Drs R Reichenbach and H McDonald of the Army and of the NASA, Ames Research Center respectively

REPORTS AND PAPERS

1. S R N De Zilwa, S Sivasegaram and J H Whitelaw (1997) Flow instability and oscillations in isothermal and reacting plane sudden-expansion flows. Imperial College, Mechanical Engineering Report TF/97/08, extended as TF/97/09.

2. C Poppe and J H Whitelaw (1997) Rayleigh scattering in open and ducted flames. Imperial College, Mechanical Engineering Report TF/97/18.

3. S R N De Zilwa, S Sivasegaram and J H Whitelaw (1997) Active control of isothermal and combusting flows in plane sudden-expansions. Imperial College, Mechanical Engineering Report TF/97/09. Also, Proc 10th International Symposium on Transport Phenomena, Kyoto, 325-330.

4. S R N De Zilwa, L Khezzar and J H Whitelaw (1998) Plane sudden expansion flows. Imperial College, Mechanical Engineering Report TF/98/05.

5. S R N De Zilwa and J H Whitelaw (1998) Visualisation of jets inclined to a cross flow. Imperial College, Mechanical Engineering Report TF/97/27. Also, Proc 8th International Symposium on Flow Visualisation.

6. R Bhidayasiri, S Sivasegaram and J H Whitelaw (1997) Control of combustion oscillations in a gas turbine combustor, Proceedings of the Seventh Asian Congress of Fluid Mechanics, pp. 107-109.

7. R Bhidayasiri, S Sivasegaram and J H Whitelaw (1998) Control of oscillations in premixed gas-turbine combustors. Imperial College, Mechanical Engineering Report TF/98/08. Also, in Advances in chemical propulsion, edited by G D Roy.

8. S R N De Zilwa, S Sivasegaram and J H Whitelaw (1997) Combustion oscillations in plane and round sudden expansion flows. Mechanical Engineering Report TF/98/09.

9. Y Hardalupas, A Selbach and J H Whitelaw (1998) Aspects of oscillating flames. J of Visualisation, **1**, 1-16.

10. K Sardi, A M K P Taylor and J H Whitelaw (1998) Extinction of turbulent counterflow flames under periodic strain. Mechanical Engineering Report TF/97/20. Combustion and Flame, in press.

11. K Sardi, A M K P Taylor and J H Whitelaw (1997) A mixing model for joint scalar statistics. Mechanical Engineering Report TF/97/22. Combustion Science and Technology, in press.

12. K Sardi, A M K P Taylor and J H Whitelaw (1997) A mixing model for the calculation of extinction in oscillating flames. Mechanical Engineering Department Report TF/97/19. Accepted for presentation at the 29th AIAA Fluid Dynamics Conference. Under consideration by the AIAA Journal.

13. K Sardi and J H Whitelaw (1998) Extinction timescales of periodically strained, lean counterflow flames. Mechanical Engineering Report TF/97/20. Under consideration by the Journal of Experiments in Fluids.

APPENDIX A
Descriptions of tasks

1. Arrange two-dimensional, plane ducted flow with sudden expansion, an upstream contraction, arrangement for loudspeaker at upstream end, measured methane gas and air flows to allow wide ranges of premixed equivalence ratio and Reynolds number, and variable downstream length.

Evaluate isothermal flows of air in terms of flow visualisation and velocity characteristics and establish the range of two-dimensional mean flow in terms of Reynolds number and corner-vortex effects.

With premixed fuel and air, conduct experiments as a function of equivalence ratio, for a small number of Reynolds numbers, to establish the acoustic characteristics of the flows. Duct length will also be a variable. These experiments will involve wall-pressure and free-field sound measurements.

2. Arrange instrumentation for the measurement of local velocities, temperatures, heat fluxes. This will involve laser-Doppler velocimetry, Rayleigh scattering and small-diameter digitally compensated thermocouples, the provision of suitable software for heat-flux measurements and comparison of the accuracy of measurements involving Rayleigh scattering and thermocouples. Laser-induced fluorescence of the OH radical will be used to complement the local heat flux results.

In addition, standard instrumentation will be used for the measurement of local species concentrations in conjunction with quartz suction probes. It will comprise unburned hydrocarbons by flame ionisation detection, oxides of carbon by infrared detection, oxides of nitrogen by chemie luminescence, oxygen by a paramagnetic meter and hydrogen by chromatography.

3. Arrange the flow with the highest Reynolds number and an equivalence ratio which does not give rise to acoustic oscillations and measure the properties referred to in paragraph 2 in sufficient detail to provide sufficient information to define the flow and to ensure that the accuracy of measurements is more than adequate. Repeat these measurements at a lower Reynolds number, still assumed to give rise to turbulent flow, so as to check possible buoyancy effects on overall and local flow properties. These measurements will be extensive and carefully conducted so that they are suitable for the evaluation of calculation and will include detailed consideration of local heat fluxes and the mechanisms of diffusion.

4. With equivalence ratios which give rise to acoustic coupling, control the amplitude by feed-back control to the loudspeaker and, for acceptable amplitudes, conduct measurements similar to those of paragraph 3 with the addition of detailed consideration of spectral characteristics. Again, the experiments will be conducted for two Reynolds numbers and a smaller number of tests will be made with the length of the duct from the plane of the expansion to the exit as a variable.

Special emphasis will be placed on the extent to which the concentration of oxides of nitrogen are reduced by the amplitude of the oscillations.

It is intended that the above research will provide information which will allow consideration of flows with equivalence ratios close to the lean flammability limit, as in modern gas turbines, and the extent to which local stretch can lead to increase in amplitude of imposed oscillations and to extinction. This type of flow is likely to be another which can make use of active control and it is hoped that this suggestion can be pursued in future work.

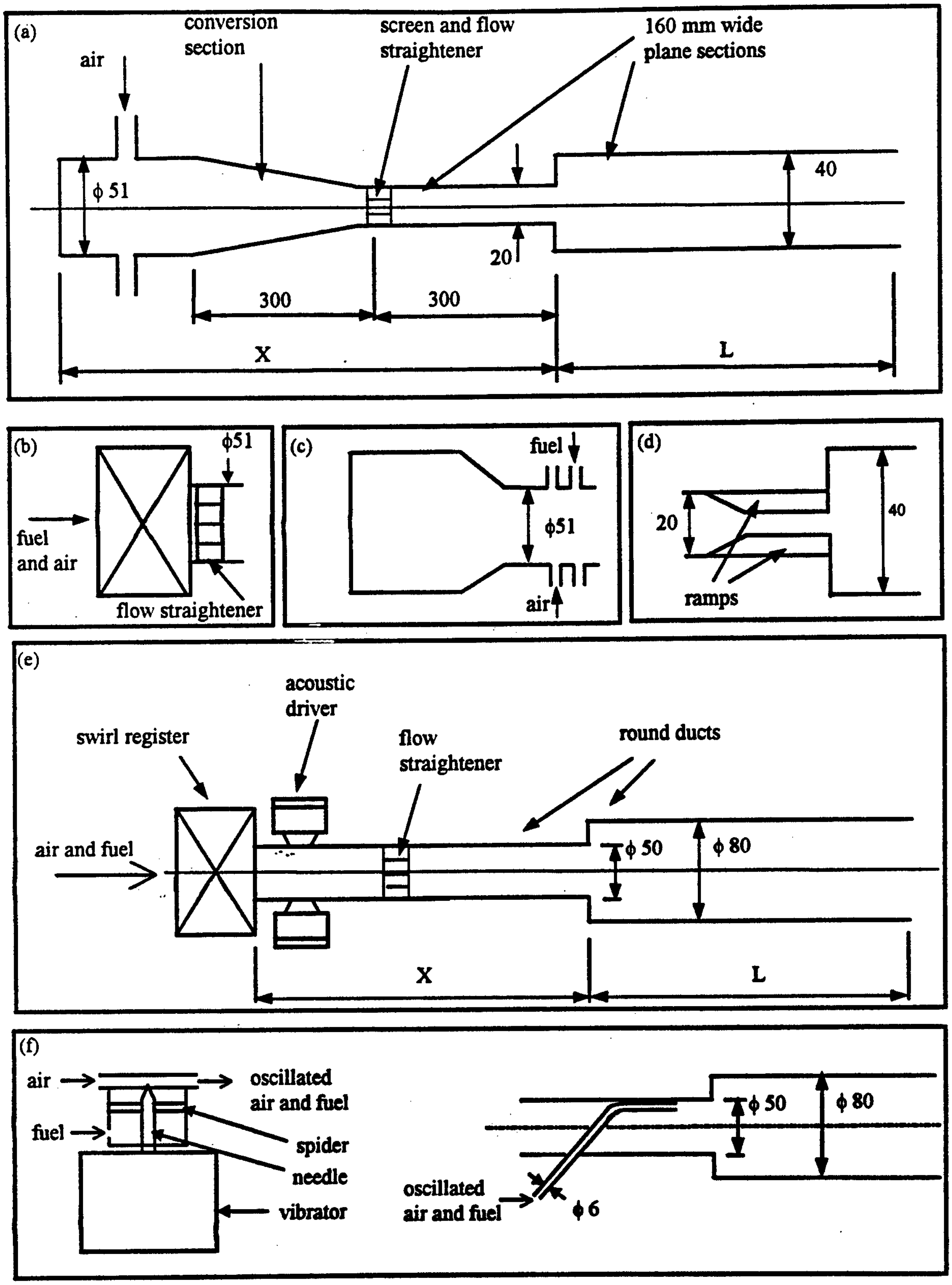


Figure 1: Sudden-expansion flow arrangements:
(a) plane configuration for isothermal flow with (b) swirl register for combusting flow, (c) loudspeaker to provide oscillations and (d) arrangement for increasing area ratio;
(e) axisymmetric configuration with acoustic drivers and (f) the arrangement for oscillating the fuel.

(a)

(b)

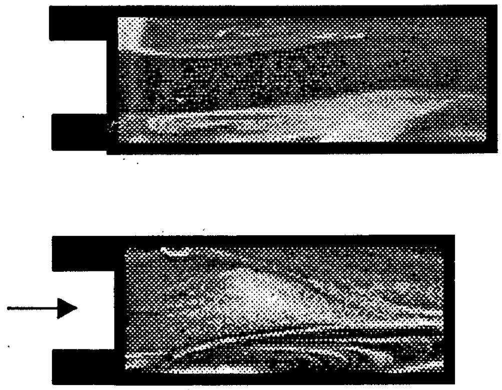


Figure 2: Visualisation of isothermal plane sudden-expansion flow.
Acoustically open upstream end; X = 980 mm, L = 680 mm; upstream duct height = 20 mm, downstream duct height = 40 mm, area ratio = 2.0.
(a) Smoke visualisation with Re = 600, and
(b) Visualisation by a plate coated with pigment with Re=20000.

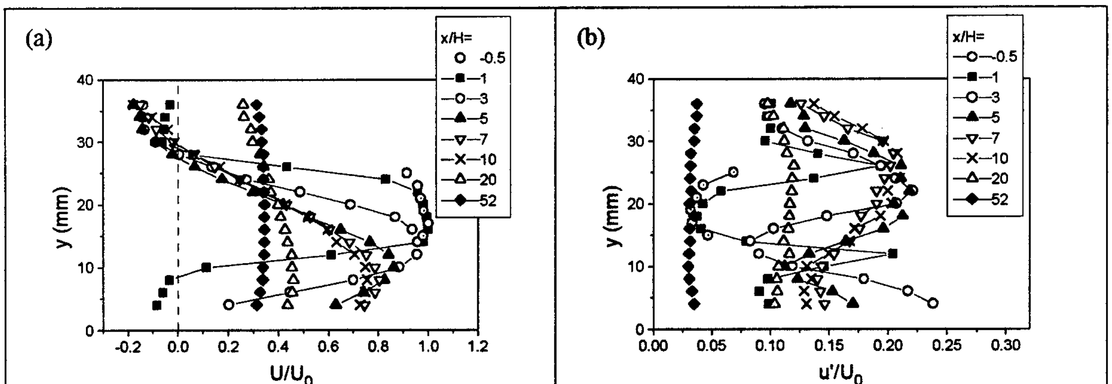


Figure 3: Velocity characteristics of isothermal plane sudden-expansion flow.
Acoustically open upstream end; X = 980 mm, L = 680 mm; upstream duct height = 14 mm, downstream duct height = 40 mm, area ratio = 2.86.
(a) mean and (b) rms velocities.

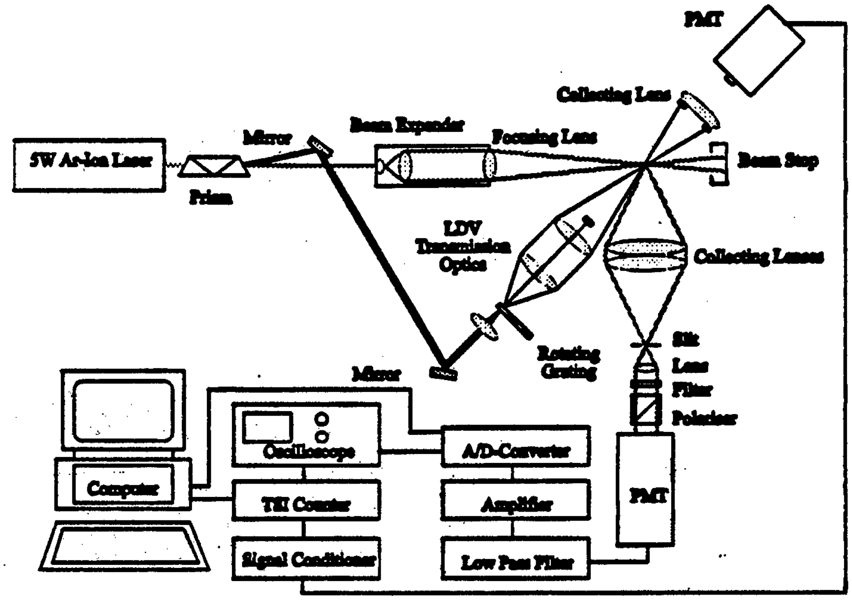


Figure 4: Arrangement for combined laser Rayleigh scattering and laser Doppler anemometry measurements.

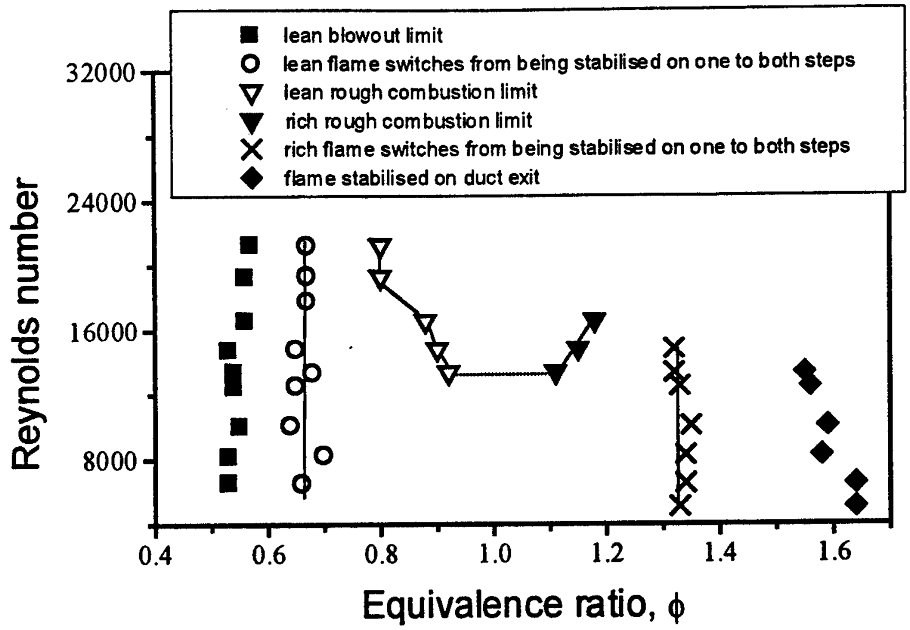


Figure 5: Flame stability limits of plane sudden-expansion flow.
Acoustically open upstream end; X = 980 mm, L = 680 mm; upstream duct height = 14 mm, downstream duct height = 40 mm, area ratio = 2.86.

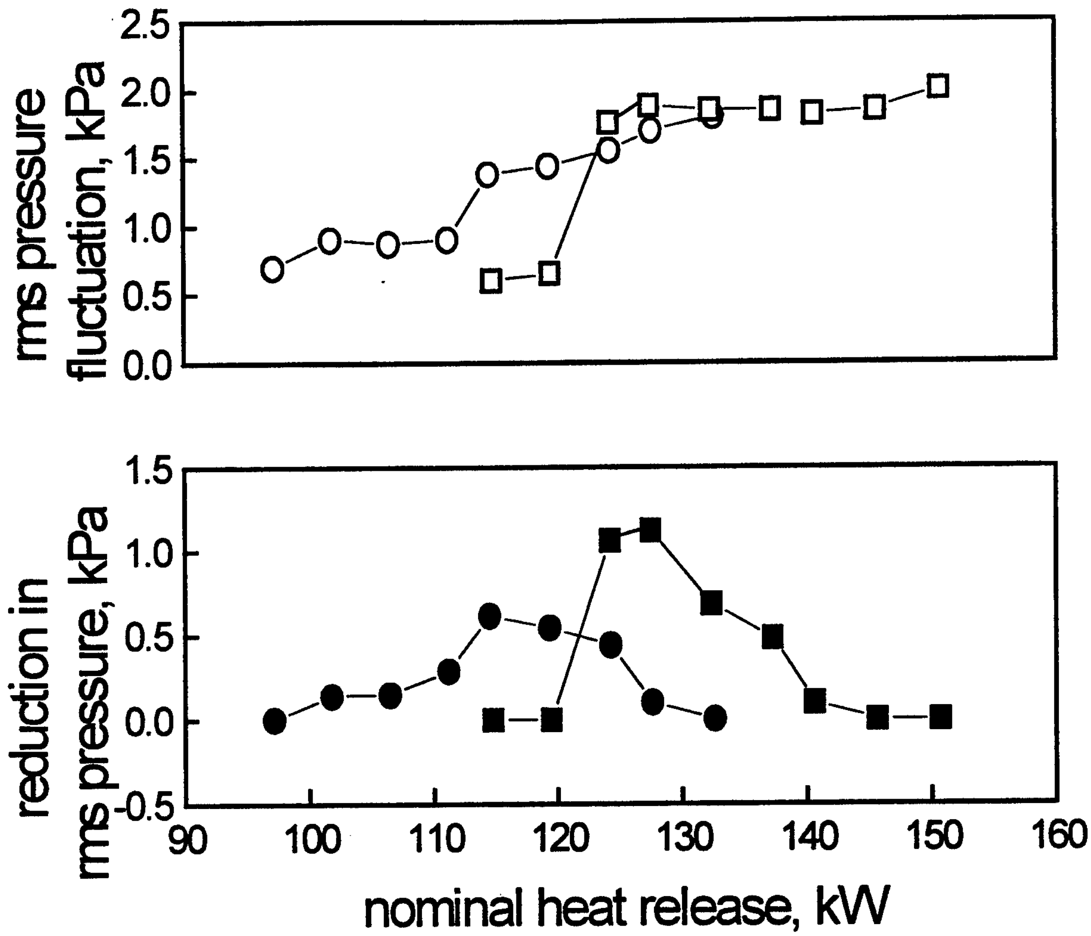


Figure 6: Amplitude without and attenuation by active control of oscillations in plane sudden-expansion flow.
Acoustically open upstream end; X = 980 mm, L = 680 mm; upstream duct height = 14 mm, downstream duct height = 40 mm, area ratio = 2.86, dominant frequencies=150-160 Hz.

○● Re=16,000,

□■ Re=20,000.

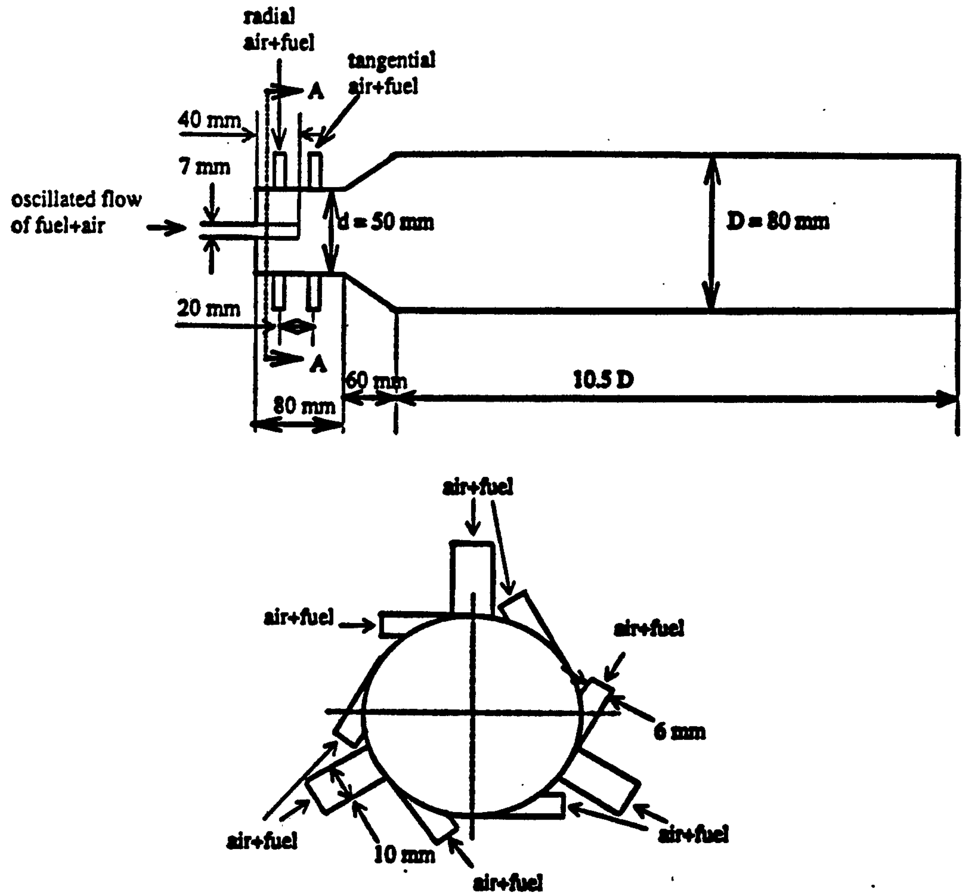
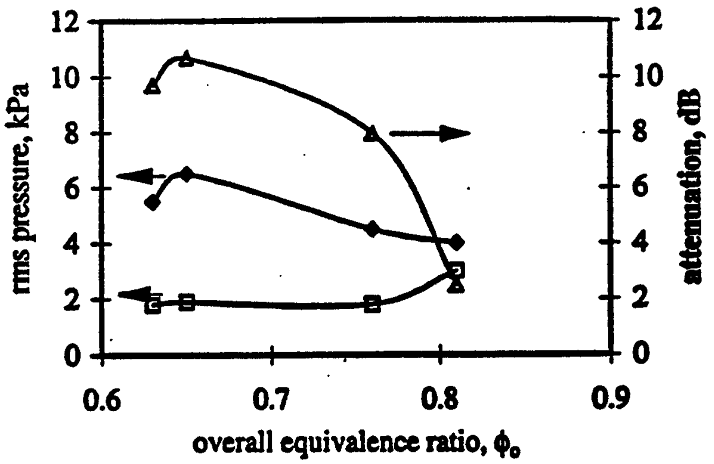


Figure 7: Swirl burner.

(a)



(b)

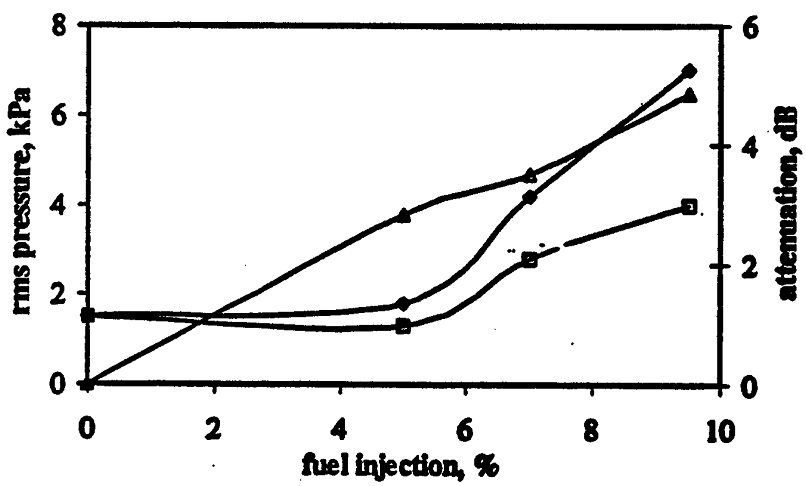


Figure 8: Control of oscillations in the swirl burner.

(a) by oscillating central axial fuel-air jet; Sw = 1.35, Re = 56,000, velocity of main flow = 17 m/s, velocity of pilot stream = 42 m/s; 5% of total fuel oscillated;

(b) by oscillating fuel in the main flow; Sw = 0.60, Re = 56,000, velocity of main flow = 17 m/s, velocity of pilot stream = 60 m/s; equivalence ratio of pilot stream and tangential and radial jets = 0.73.

◇ without control; □ with control; Δ attenuation

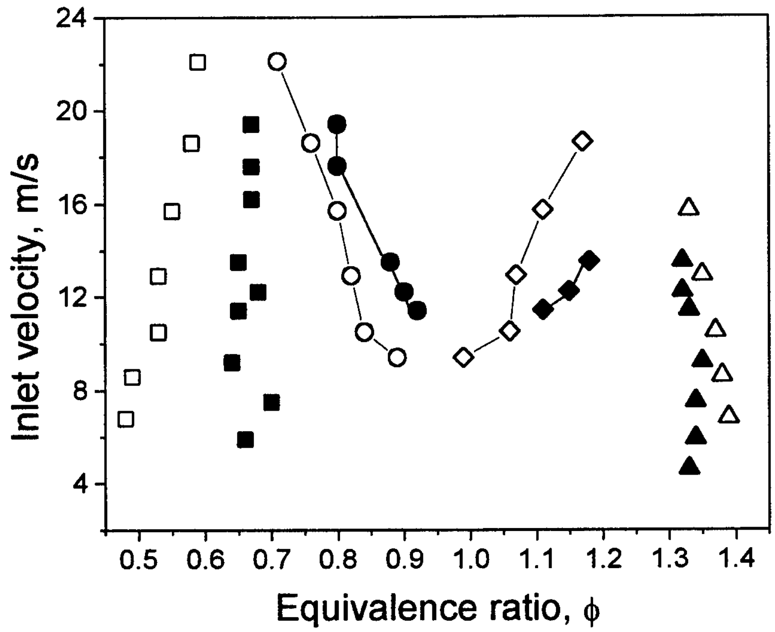


Figure 9: Flame stability limits in plane and axisymmetric configurations.
Acoustically open upstream ends;
Axisymmetric duct: X = 8D, L = 10.5D, area ratio = 2.5;
Plane duct: X = 980 mm, L = 680 mm, area ratio 2.86.

Axisymmetric duct (open symbols):
square - lean limit at which flame is stabilised by expansion
circle - lean large-amplitude combustion limit
diamond - rich large-amplitude combustion limit
triangle - rich limit at which flame is stabilised by expansion

Plane duct (solid symbols):
square - lean limit at which flame is stabilised by both steps
circle - lean large-amplitude combustion limit
diamond - rich large-amplitude combustion limit
triangle - rich limit at which flame is stabilised by both steps

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	22 May 1998	Final Report; December 1996 to May 1998

4. TITLE AND SUBTITLE

Flow and turbulence characteristics of separated flows with active control.

5. FUNDING NUMBERS

6. AUTHOR(S)

J H Whitelaw

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Thermofluids Section, Mechanical Enginering Department
Imperial College of Science, Technology and Medicine
Exhibition Road, London SW7 2BX.

8. PERFORMING ORGANIZATION REPORT NUMBER

TF 98/11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Dr R Reichenbach, USARDSG, 233 Old Marylebone Road
London NW1 5TH

10. SPONSORING /MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

None

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Experiments have been carried out in plane and axisymmetric sudden-expansion flows to quantify velocity characteristics in isothermal and reacting flows and temperature and emission characteristics in the reacting flows, to establish flammability and stability limits, to determine the acoustic characteristics and their importance to large-amplitude oscillations and to examine the nature of extinction. Flow visualisation and detailed measurements quantified the asymmetry of the plane flows and the extent to which it was removed by combustion. Longitudinal waves dominated the flows in both ducts for an extensive range of equivalence ratios and active control was successful in reducing amplitudes except where the frequencies were broad band as at higher equivalence ratios and close to flammability limits. Close to these limits, oscillations existed with frequencies much lower than those associated with acoustic or bulk-mode frequencies and with modulation rather than the single-frequency oscillations associated with equivalence ratios between around 0.75 and 1.2.

Models of the combustor of a land-based gas turbine were examined, one with an annular main flow and a central pilot flow and the other with swirl stabilisation. In the first arrangement, the movement of flame stabilisation from the annular ring to the back step was important and, in the latter, the position of stabilisation also moved but this time axially with increasing load so that the fixed position of the actuator for active control proved to be satisfactory for some load conditions and less so for others.

14. SUBJECT ITEMS

Sudden expansion flows; combustion oscillations, extinction and control; gas turbine combustors.

15. NUMBER OF PAGES

18 inc figs

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

ATTACHMENT 1 PAGE 1